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LLC 공진형 컨버터의 설계

최항석
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Design Consideration of LLC resonant converter

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ABSTRACT

This paper presents design consideration for LLC resonant converter utilizing the leakage inductance and magnetizing inductance of transformer as resonant components. The leakage inductance in the transformer secondary side is also considered in the gain equation. The design procedure is verified through experimental results.

1. Introduction

The Conventional PWM technique processes power by controlling the duty cycle and interrupting the power flow. All the switching devices are hard-switched with abrupt change of currents and voltages, which results in severe switching losses and noises. Meanwhile, the resonant technique process power in a sinusoidal form and the switching devices are softly commutated. Therefore, the switching losses and noises can be dramatically reduced with resonant technique. For this reason, resonant converters have drawn a lot of attentions in various applications.

Among many resonant converters, half-bridge LLC-type multi-resonant converter has been the most popular topology for many applications since this topology has many advantages over other topologies; it can regulate the output over wide line and load variations with a relatively small variation of switching frequency, it can achieve zero voltage switching (ZVS) over the entire operating range, and all essential parasitic elements, including junction capacitances of all semi-conductor devices and the leakage inductance of the transformer, are utilized to form multi-resonant network. Even though a lot of researches[1-6] have been done on the LLC resonant converter topology so far, most of the previous researches simplified the AC equivalent circuit by ignoring the leakage inductance in the secondary side, which results in incorrect gain equation. This paper presents the basic operation principle and practical design procedure considering the leakage inductance in the transformer secondary side. The design procedure is verified through an experimental prototype converter.

2. Operation Principle and Fundamental Approximation

Figure 1 shows the simplified half-bridge LLC resonant converter and Figure 2 shows its waveforms. The half-bridge totem pole composed of Q1 and Q2 applies a square wave voltage (Vd) to the resonant network. Since the resonant network has the effect of filtering the higher harmonic voltages, essentially, a sinusoidal current is appears in the resonant network. The current is lagging the voltage applied to the resonant network (that is, the fundamental component of the square wave applied by the half-bridge totem pole), which enables the MOSFETs to be turned on with zero voltage. As can be seen in Figure 2, the turn-on switching loss is removed by turning on the MOSFET while the current is flowing through the anti-parallel diode.

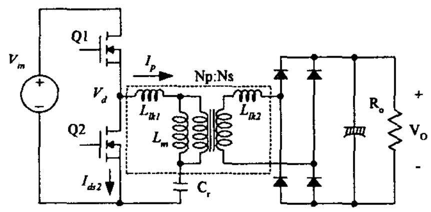

Fig. 1 A simplified Half-bridge LLC resonant converter

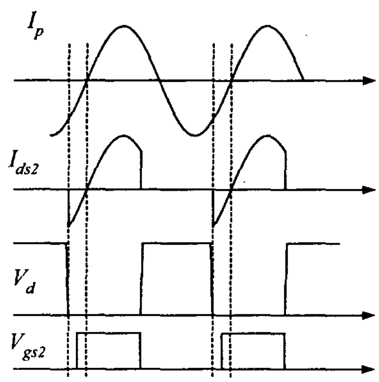

Fig. 2 Typical waveforms of LLC resonant converter

Even though the resonant network is driven with square wave voltage, near sinusoidal current is flowing through the resonant network due to the filtering action of the resonant network. This allows the classical fundamental approximation to be used to obtain the voltage gain of the resonant converter, which assumes that only the fundamental component of the square-wave voltage input to the resonant network contributes to the power transfer to the output. Figure 3 shows how this equivalent load resistance is derived. The equivalent load resistance shown in the primary is obtained as

$$R_{ac}=\frac{8n^2}{\pi^2}R_o \tag{1}$$

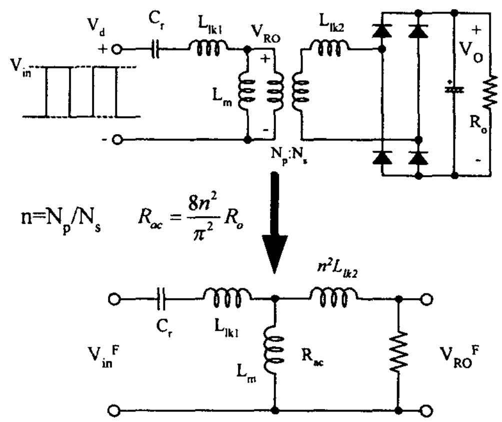

Fig. 3 AC equivalent circuit of LLC resonant converter

With the equivalent load resistance obtained in (1), the characteristics of the LLC resonant converter will be derived. Using the AC equivalent circuit of Fig. 3,. the voltage gain is obtained as

$$M=\frac{2n\cdot V_O}{V_{in}}=\left|\frac{-\omega^2L_mR_{ac}C_r}{j\omega\cdot(1-\frac{\omega^2}{\omega_o^2})\cdot(L_m+L_{lks})+R_{ac}(1-\frac{\omega^2}{\omega_m^2})}\right| \tag{2}$$

where

$$R_{ac}=\frac{8n^2}{\pi^2}R_o\ ,\ L_p=L_m+L_{lkp}\ ,\ L_{eq}=L_{lkp}+L_m\,//\,L_{lks}$$

$$\omega_o=\frac{1}{\sqrt{L_{eq}C_r}}\ ,\ \omega_m=\frac{1}{\sqrt{L_pC_r}}$$

$$k=\frac{L_p}{L_{eq}}\ ,Q=\sqrt{\frac{L_{eq}}{C_r}}\frac{1}{R_{ac}}$$

The equation (2) is plotted in Figure 4 in the case when the ratio between L_m and L_{lks} is 5, where the x-axis is normalized switching frequency (w/w_o). As can be observed, higher gain is obtained as Q decreases (as the load decreases). Therefore, the transformer turns ratio should be determined under full load condition. One interesting thing observed in Figure 5 is that the gain is fixed at resonant frequency (w_o) regardless of the load variation, which is given as

$$M=\frac{L_m}{L_p-L_{eq}}=\frac{L_m+L_{lks}}{L_m},\ when\ \omega=\omega_o \tag{3}$$

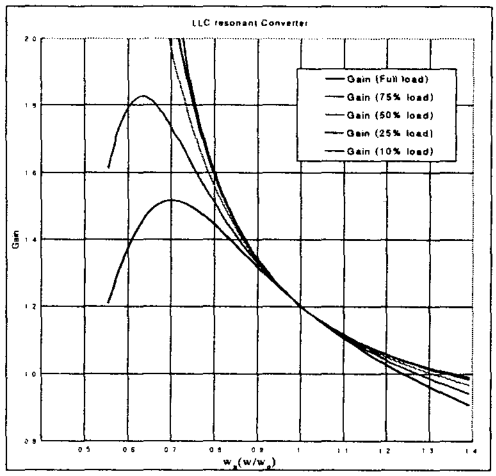

Fig. 4 Typical gain curves of LLC resonant converter

The LLC multi-resonant converters show nearly load independent characteristics when the switching frequency is around the resonant frequency. This is a distinctive advantage of LLC-type multi-resonant converter over conventional series-resonant converter. Therefore, it is typical to operate the converter around the resonant frequency to minimize the switching frequency variation at light load condition.

3. Experimental Results

Based on the design equation of (2), design was done for the 25V/4.5A output power supply (112.5W). The input voltage is 220Vac~270Vac (290~380Vdc). The resonant frequency is designed as 84kHz with Lp=800uH, Leq=200uH and Cr=18nF. The converter is designed to operate around the resonant frequency to minimize the switching frequency variation at light load condition. The gain curves are shown in Fig. 5.

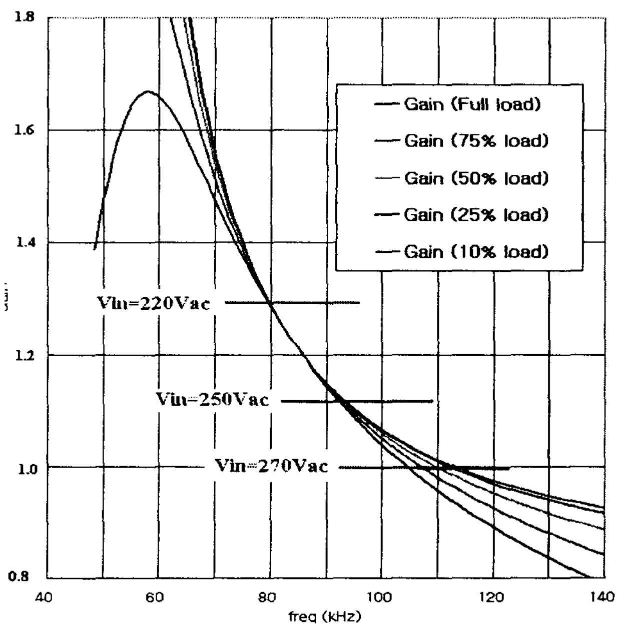

Fig. 5 Gain curves with designed resonant parameters

Experimental board had been built and tested. The schematic is shown in Fig 6 and the key components are as belows:

- Lp=800uH, Leq=200uH, Cr=18nF, fo=86kHz
- Transformer : EER3541:Lp=800uH,Leq=200uH, Np=52T, Ns1=Ns2=7T

-MOSFET : FQPA12N60, Diode : MBRF20100CT

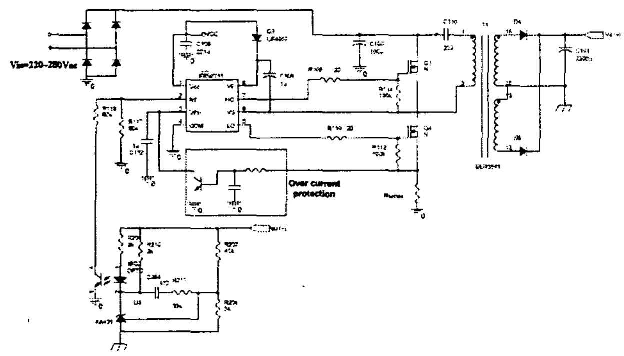

Fig. 6 Schematic of the test board

Figure 7 and 8 show the operation waveforms for full load condition with input voltage of 220Vac and 270Vac, respectively.

Figure 9 shows the measured efficiency and Figure 10 shows the measured switching frequency. As can be seen, the switching frequency variation is well matched with the gain curves of Fig. 5.

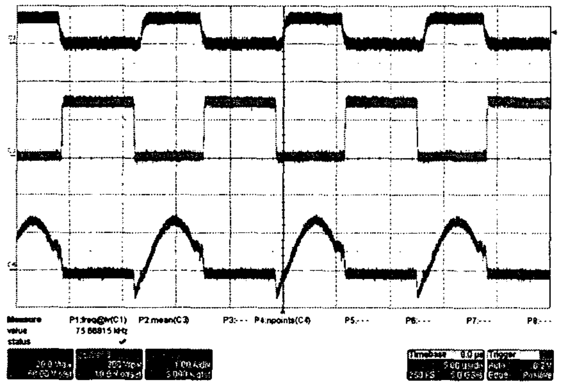

Fig. 7 Waveforms for full load condition with Vin=270Vac

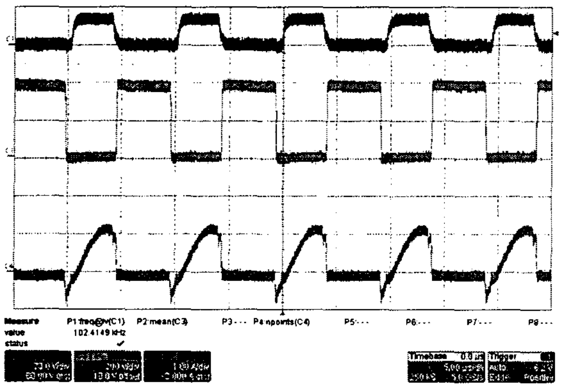

Fig. 8 Waveforms for full load condition with Vin=270Vac

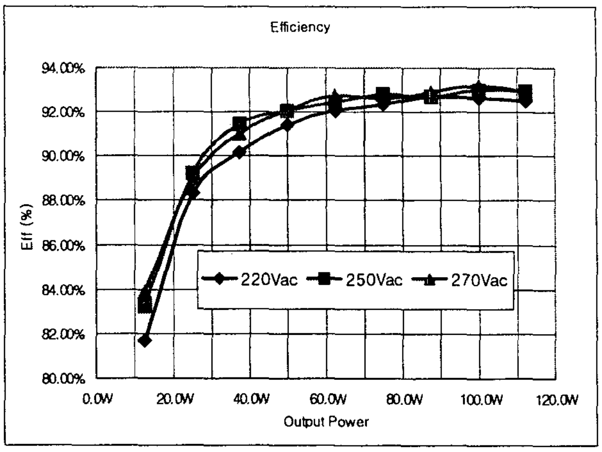

Fig. 9 Efficiency

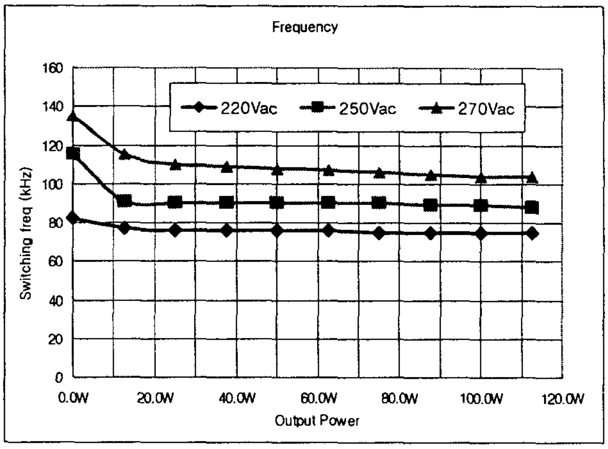

Fig. 10 Frequency variation

4. Conclusion

This paper has presented design consideration for LLC resonant converter utilizing the leakage inductance and magnetizing inductance of transformer as resonant components. The leakage inductance in the transformer secondary side was also considered in the gain equation. The design procedure was verified through experimental results.

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